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16. ABSTRACT

Mechanistic models of nutrient dynamics in natural wetlands were developed and applied in a study of Kissimmee River (Florida) flood-plain marshes. The models describe hydrodynamics and transport diffusion in wetland basins and the ecological processes of nutrient uptake, conversion to organic forms, and release from the marsh to a receiving water body. Results of computer simulations suggested that more than 50 percent of dissolved phosphorus loadings could be permanently captured by the marsh ecosystem, at least up to a loading rate of 5 $g/m^2/yr$. In addition, 80 to 90 percent of the phosphorus exported from the marsh would be transformed from dissolved to detrital forms and would therefore be relatively unavailable to nuisance algae. The simulations suggested that consolidated peat would be laid down at a rate of approximately 0.5 cm/yr, giving a useful life of the marsh of perhaps 50 to 100 years.

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NUTRIENT-UPTAKE MODEL IN MARSH ECOSYSTEMS[a]

By Lawrence A. Burns[1] and R. Bruce Taylor, III,[2] A. M. ASCE

(Reviewed by the Technical Council on Computer Practices)

INTRODUCTION

The impact of flood-control projects and construction works on wetlands is a nation-wide issue. Wetlands are valuable as wildlife habitat, and their ability to sequester nutrients offers considerable cost advantages over tertiary treatment of waste loadings. This study investigates the water-quality benefits that could accrue from careful management of wetlands in Florida's Kissimmee River basin.

Background.—The Kissimmee River is the main tributary to Lake Okeechobee, which is a major water-supply reservoir for South Florida. Increased nutrient loadings have provoked increasing concern for the trophic state of the lake (18). Prior to channelization, the Kissimmee descended 30 ft–35 ft (9 m–11 m) along its 98-mile (160-km) meandering course between Lake Kissimmee and Lake Okeechobee [Fig. 1, showing Soil Conservation Service Planning Units (PU) and Water-Control Structures (S)]. The 758-sq mile (1,960-km^2) lower basin contained few lakes or well-defined tributary channels (21). The river flood plain averaged 2 miles (3 km) in width. Normal annual fluctuation of the river was 3 ft–4 ft (1 m–1.2 m), with mean peak flows in October and lowest mean flows in May. Parts of the flood plain were inundated for as long as 5 months and, in wet years, for as long as 10 months (15). Within the flood plain, fluctuating river levels supported approx 40,600 acres (164,000,000 m^2) of marsh; 5,990 acres (24,300,000 m^2) of pasture, mainly unimproved; and 4,750 acres (19,200,000 m^2) of open water and ruderal communities (22).

In April, 1962, the Corps of Engineers began construction of a flood-control

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project that, upon completion in July, 1971, replaced the natural river system with flood-control channel C-38. The channel is stepped down in six pools by a 6-ft (1.8-m) vertical fall over the primary control structures. Flood-plain marshes have been largely (78%) replaced by pasture, mesic shrublands, and dredging spoil (22).

Objectives.—The objectives of this study were to quantify the water-quality benefits accruing from renovation of the flood-plain marshes and to define a plan for marsh restoration and management. Two complementary models were applied to a 107-acre (430,000-m^2) example tract, the "Boney Marsh" (Fig. 1). The two modeling systems were: (1) Two-dimensional, finite difference hydromechanics and transport diffusion models; and (2) a one-dimensional (no

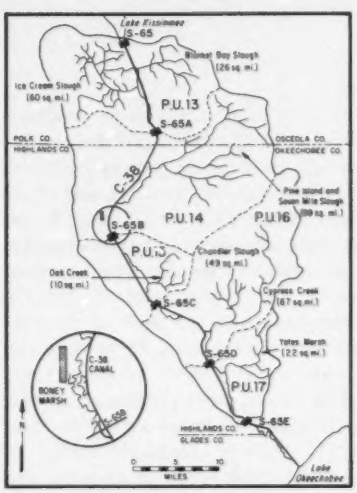

FIG. 1.—Location Map of Geography of Kissimmee River Basin (Canal C-38) and Example Marsh Tract (Boney Marsh)

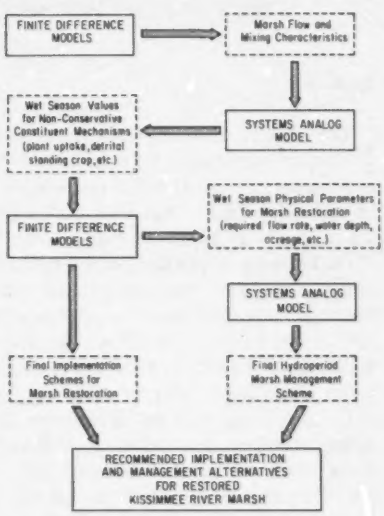
FINITE DIFFERENCE MODELS
Marsh Flow and Mixing Characteristics
Wet Season Values for Non-Conservative Constituent Mechanisms (plant uptake, detrital standing crop, etc.)
SYSTEMS ANALOG MODEL
FINITE DIFFERENCE MODELS
Wet Season Physical Parameters for Marsh Restoration (required flow rate, water depth, acreage, etc.)
SYSTEMS ANALOG MODEL
Final Implementation Schemes for Marsh Restoration
Final Hydroperiod Marsh Management Scheme
RECOMMENDED IMPLEMENTATION AND MANAGEMENT ALTERNATIVES FOR RESTORED KISSIMMEE RIVER MARSH

FIG. 2.—Flow Diagram of Model Applications and Interfacing

spatial grid), continuous ecosystem analysis model (analog computer). The flow of information between the two modeling systems is indicated in Fig. 2. The information provided by one model for use by the next is shown within the dashed outlines.

The finite difference models were first applied to determine the marsh flow and mixing characteristics as a function of water depth, discharge rate, percentage of point and nonpoint loadings, and volume of water on the marsh. The ecosystem model used these results for calibration of its (spatially aggregated) kinematic wave representation of marsh hydraulics. Analog simulations of nutrient dynamics then provided the finite difference models with numerical values (constants) for nonconservative (with respect to the surface water mass) marsh source/sink mechanisms for nutrients and organic matter under high load conditions during

the wet season. These values included rates of uptake of nutrients by plants, standing stocks of nutrients and organic matter, rate of oxidation of detrital materials, and the (oxidation) coupled release of detrital nutrients to dissolved nutrients in the water column. These values were then used by the finite difference models to determine the wet season flow parameters that would provide maximum water-quality benefits. The wet season flow parameters were used to develop a marsh restoration scheme.

Models

Ecosystem Model.—Fig. 3 is an ecosystem circuit diagram (20) of ecological dynamics in the Kissimmee River flood-plain marshes. (The PO_4 is dissolved phosphate, and P is phosphorus in associated biotic compartments.) Input-forcing functions include rainfall and gravity-driven runoff from surrounding uplands that contribute water to the marsh (compartment labeled "marsh water"). Both

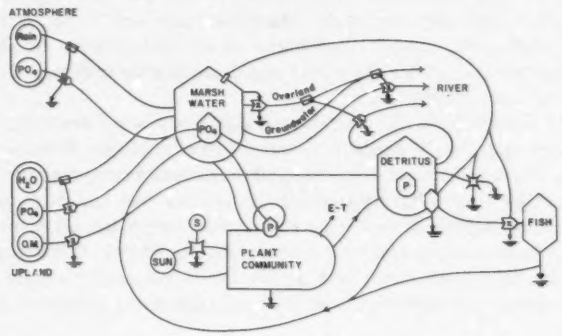

FIG. 3.—Ecosystem Circuit Diagram of Ecological Nutrient Dynamics in Marshlands

rainfall and upland runoff carry a load of dissolved phosphate that increases the total standing crop of dissolved phosphorus on the marsh (compartment labeled PO_4 within the marsh water compartment). Upland runoff also carries a load of organic debris and combined phosphorus that enters the "detritus" compartment of the model. Water is exported from the marsh by ground water (subsurface) and overland flow toward the river and by evapotranspiration (E-T) losses to the atmosphere.

In the model, both overland and subsurface flow export phosphorus, with loads determined by the dissolved phosphate concentration in the standing water on the marsh. Overland flows also carry detritus and organic particulate P out of the marsh. The plant community was represented by a compartment that includes both biomass (standing crop) and phosphorus contained in plant tissues. The plant community includes perennial rooted macrophytes and annual plants that are seasonally active when conditions permit their development. Specifically, based on the behavior of wild millet in the Kissimmee basin (14), annuals were only active when a dry down of at least 6 weeks (to permit germination of

seed present in the soil) occurred during the growing season (mid March to early September). It was also assumed that, in a naturally functioning marsh, about 25% of the marsh area would be dominated by annual plants and about 75% by perennials. Although the precise percentage of area occupied by annual plants is unknown, the idea that annuals were an important component of the original marsh is supported by the former presence of wintering ducks that feed on seed production by annuals (15).

Detritus forms the primary basis for the food chain that supports forage-fish populations on the marsh. During dry downs these small fishes are concentrated in pools and forced toward the river channel where they are available to game fishes and wading birds. Plant litter is the major source of detrital materials on the marsh. In the model, the food resource available to fishes was represented as increasing with the increasing water stage, primarily by a reflooding of additional marsh area that would provide increments in the space and total resources available to the population.

The water stage on the marsh also controls important aspects of detrital dynamics. First, biochemical oxidation of detrital and soil organic matter on the marsh is accelerated under dry conditions (26) and forces at least partial release of organically bound phosphorus to solution phases. In addition, dry downs remove detritus from the active marsh surface by settling and compacting the loose materials to form soil.

A set of seven first-order differential equations were developed from this ecosystem model (Fig. 3) and parameterized from published literature on marsh processes. The equations were mechanized on an analog computer and simulations were driven by four arbitrary-function generators that had been programmed with measured climatic data for the Kissimmee region [monthly mean rainfall, pan evaporation rates, insolation (seasons), and discharge]. Conceptual development of the functional forms and derivation of parameter values is given in Ref. 5; equations and numerical values of parameters are presented in Appendix I.

Finite Difference Models.—Two finite difference models were used to solve the vertically integrated, two-dimensional equations of: (1) Fluid motion and continuity; and (2) transport diffusion. These equations represent the physical laws describing movement and mixing of two-dimensional fluid flows driven by dynamic mechanisms such as gravity, bottom friction, and lateral shear. Solutions were obtained using numerical techniques described by Yanenko (27), Abbott (1), and Richtmyer and Morton (23), combined with the physics of two-dimensional flows as treated in Refs. 7 and 25. A detailed description of these finite difference models is given in Ref. 24.

Hydromechanics.—The hydromechanics model generated, for later use in the transport diffusion model, the steady-state, two-dimensional marsh flow field, including depth-integrated velocity components and dynamic free water-surface elevations for such prescribed conditions as inflow, rainfall, and stillwater level (SWL). The hydromechanics model solved the vertically integrated, two-dimensional equations of fluid motion and continuity for the depth-integrated velocity components in the horizontal plane, q_x and q_y, and the dynamic free surface elevation of the water column, η.

Fig. 4 shows the grid matrix used for both the hydromechanics and the transport diffusion model. Solutions for η, q_x, and q_y were calculated for each grid

element with η located at the center of each grid, q_x (shown acting positive) centered on the left-hand side, and q_y (positive) centered on the lower side of each element. The equations solved by the hydromechanics model are presented in Appendix I. The equations of motion in the x and y directions were solved

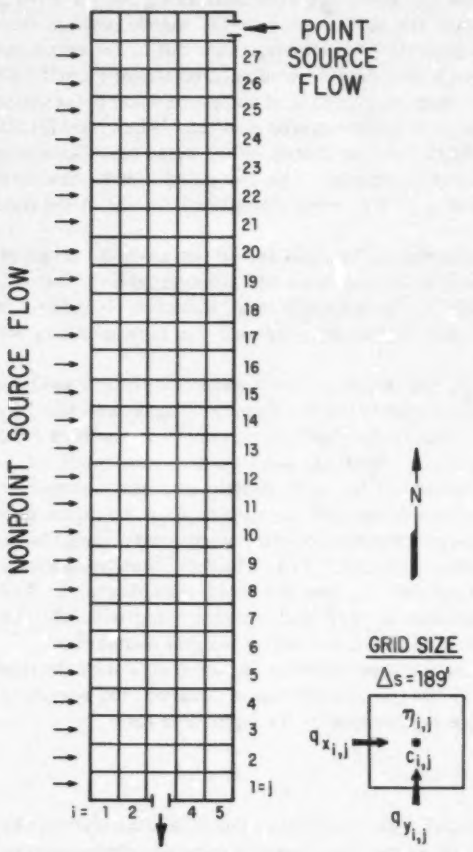

FIG. 4.—Grid Schematic for Spatially Distributed Digital Computer Models of Boney Marsh Tract

for q_x and q_y, respectively, while the equation of continuity was solved for η.

In performing a simulation, the elevation of each grid element above mean sea level (MSL); the marsh SWL; bottom friction; rainfall, evaporation, and seepage rates; and point source (PS) and nonpoint source (NPS) flow rates were read into the model. The model then compared the grid elevations with

the SWL to determine the stillwater depth h for each grid element. Grids with elevations above the SWL were inactivated as dry portions of the marsh. At time $t = 0$, all q_x, q_y, and η values were set to zero, except the prescribed PS and NPS flows. This began the simulation under quiescent conditions, with the free surface at the SWL and no flow. The computations were then allowed to generate, with the governing equations being solved at each grid element every 4 min, until the flow regime in the marsh reached steady state. This was observed when: (1) The computed flow out of the marsh equaled the total flow into the marsh, including the combined effects of PS and NPS flow, rainfall, evaporation, and seepage; (2) the total volume of water in the marsh had stabilized and the dynamic free surface profile was established; and (3) flow components had stabilized throughout the marsh. When these conditions were satisfied, the simulation run was completed. The computed steady-state values of q_x, q_y, and total depth $D = \eta + h$, were stored for later use in the transport diffusion model.

The hydromechanics simulations solved the unsteady forms of the governing equations (Appendix I), and were therefore capable of handling time-varying hydrologic conditions. In this application, however, fixed (time invariant) inputs were specified, and the model generated the corresponding steady-state flow conditions.

Transport Diffusion Model.—The transport diffusion model computed concentrations of constituents for the flow conditions prescribed by the hydromechanics model. Constituent loadings entering the marsh in PS and NPS flows and in rainfall were specified, and account was taken of nonconservative source/sink mechanisms for each constituent. The transport diffusion model solved the vertically integrated, two-dimensional transport diffusion equation to determine the concentrations of three constituents, using the same grid scheme as the hydromechanics model (Fig. 4). The three constituents were detrital carbon c_1, detrital phosphorus c_2, and dissolved phosphorus c_3. The concentration variable was centered in each grid element along with all source/sink terms. Flow-dependent terms were located on the grid boundaries.

The form of the transport diffusion equation solved by the model is presented in Appendix I. In the transport diffusion equation, the advective terms $\bar{u}\,\partial c/\partial x$ and $\bar{v}\,\partial c/\partial y$ were represented by the equivalent form

$$\frac{\partial}{\partial y}(\bar{u}\,\bar{c}) + \frac{\partial}{\partial y}(\bar{v}\,\bar{c}) - \bar{c}\,\frac{\partial \bar{u}}{\partial x} - \bar{c}\,\frac{\partial \bar{v}}{\partial y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

For the steady-state flow conditions used in this simulation, the last two terms reduce to zero. When the flow assumes unsteady characteristics, however, this treatment of the advective terms satisfies the requirement of zero concentration change within a grid element due to divergent (outward) flow components. (A detailed analyses is given in Ref. 25.)

Each run of the transport diffusion model was begun by prescribing source/sink parameters; constituent concentrations in the PS and NPS flows, rainfall, and seepage; hydromechanic flow conditions (from hydromechanics model); and initial constituent concentrations in the marsh. The model then computed new concentrations for every grid element, fluxes of constituents across the external boundaries, and the total mass of constituent remaining in the marsh at each time step.

Simulation Results

Marsh Residence Time Analysis.—The effects of a marsh on water quality are in part a function of the length of time the water spends on the marsh (residence time, T_r). In this study, T_r was defined as the time required for 99% of the initial water mass to be displaced by incoming water. Residence time is often defined as the volume/discharge ratio, V/Q, for poorly mixed (plug flow) basins. Conversely, for a perfectly mixed basin, the 99% washout

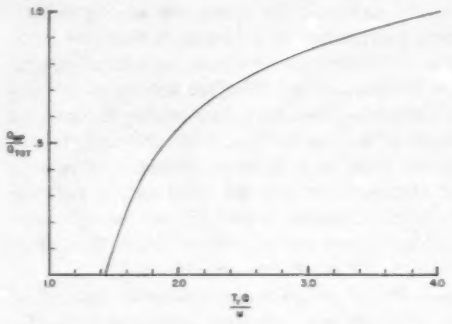

FIG. 5.—Plot of Dimensionless Residence Time Parameter ($T_r Q/V$) Versus Fraction of Total Flow Entering Marsh as NPS (Q_{NP}/Q_{TOT})

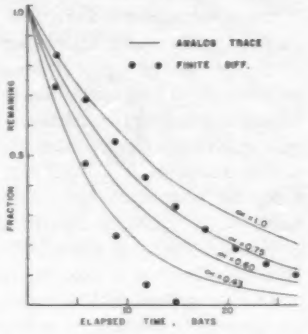

FIG. 6.—Disappearance of Initial Unit Concentration of Dissolved Material in Water Column of Shallow Basin

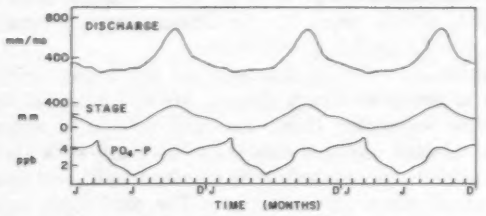

FIG. 7.—Ecosystem Simulation Results for Natural (Prechannelization Conditions) Marsh Community

time is $[-\ln(0.01)]\, V/Q = 4.6\, V/Q$. The behavior of natural basins lies between these limiting cases. To analyze flow and mixing (T_r) in the Boney Marsh, 34 runs of the hydromechanics and transport diffusion models were made for differing discharges, water depths, and percentages of PS and NPS loadings. The PS loadings were entered at the head of the marsh, and NPS loads were introduced along the lateral boundary (Fig. 4). These simulations indicated that: (1) Variation in mean depth of flow (an output of the model) had little effect on residence time for a given V/Q; and (2) residence time T_r increased significantly with increases in the percentage of flow entering the marsh as an NPS. The

latter result arose from differences in the flow field generated by PS versus NPS loadings. The PS flow field was relatively uniform, whereas the NPS flow field increased gradually from a region of low momentum in the upper reaches to a region of high momentum in the lower portion of the marsh.

Fig. 5 is a graph of dimensionless parameter $T_r Q/V$ versus Q_{NP}/Q_{TOT}, the fraction of total flow Q_{tot} entering the marsh as an NPS load Q_{NP}. From this graph, if two of the variables (residence time, V/Q, or PS/NPS source flow distribution) are known, the third can be found. This information was used to determine optimal flow regimes in restored marshes.

These simulations were also used to calibrate the ecosystem analog model. In this model, marsh hydraulics were represented by a kinematic wave approximation (9), and transport of dissolved constituents was governed by concentrations averaged over the entire marsh. A dimensionless "effective mixing ratio" (α) for the marsh basin was defined by comparing the output from analog simulations with equivalent output from the finite difference models. From this comparison α was taken as 0.75. [In Fig. 6 the solid lines indicate response of analog computer simulation for different mixing ratios (α) and solid circles indicate response of spatially distributed finite difference model. Upper set of finite difference results is 100% NPS load and lower set is 100% PS load. The 100% NPS simulation was used for calibration of natural flow conditions.]

Ecosystem Dynamics Simulations.—Fig. 7 presents the results of simulation of the prechannelization marshes. {Curves are unit total discharge from the marsh [1 mm/month = 2.166 cfs discharge from 16,430 ha (40,600 acres) of marsh], depth of flooding on the marsh (1 mm = 0.3937 in.), and depth-integrated ortho-phosphorus concentration in water flowing through the marsh basin.} In August, 1952, phosphate concentration was 0.060 ppm in the upper reach of the river (discharge from Lake Kissimmee), and 0.002 ppm in midreach (19). By comparison, the simulation predicts an August concentration of 0.0025 ppm P in water flowing off the marsh, for the estimated normal input concentration of 0.05 ppm.

The temporal pattern of water flow into the marsh was defined from mean monthly flows at the river mouth (United States Geological Survey records for October, 1950–September 1959). The total volume of water flowing into the marsh was adjusted during simulation to give a 6-week spring drawdown (a known feature of the prechannelization marshes), sufficient to allow germination and growth of annual plants to begin. The total input volume was then 4,800 mm of water yearly (4,800 $l/m^2/yr$), with a (simulated) peak discharge from the marsh community of 690 mm/month (1,500 cfs) in early October (Fig. 7). Hydrologic records indicated a net (1950's) October flow to the river from the lower basin of 1,800 cfs. Taking some 88% of flow as detained marsh flows (21) gives 1,584 cfs, only 5% higher than the simulation value. The deepest flooding (360 mm) of the marsh also occurs in October. Fig. 7 shows that the highest phosphate concentrations occur in early March, when the marsh is dry and oxidation of organic matter is a heavy contributor to total load.

The simulations predicted a winter low in macrophyte standing stocks of 120 g/m^2, rising to a peak in late May and early June of 300 g/m^2. This value can be compared to the mean biomass in Okeechobee marshes of 295 g/m^2, determined in June of 1974 by Nordlie, Fontaine, and Gayle (unpublished). Turning next to the phosphorus bound in plant tissues, the standing stock was

about 0.4 g/m^2 of phosphorus, which would suggest a tissue concentration of 0.33% early in the growing season and a minimum value in June of some 0.13%. These values are consistent with the range reported (3) for field populations of aquatic macrophytes (0.39%–0.09%) under similar conditions. The peak biomass of forage fishes (10 g/m^2) developed late in October. This value can be compared with an estimate of 13 g/m^2 derived from the work of Dineen, et al. (8), who studied fish population development during an experimental drawdown in pool B of the Kissimmee. Finally, the soil formation rate predicted by the model for natural conditions was 12.9 cm/100 yr [assuming a typical peat soil (4) with bulk density 0.25 g/cm^3 and 80% organic matter] Davis (6) estimated peat formation rates in the Everglades to be approx 13 cm/100 yr. The dynamics of the ecosystem simulation thus seemed in good accord with available data. Subsequent runs evaluated the effects of increased loadings on the marsh ecosystem and on water quality.

The model responded smoothly over a range of 0.05 ppm PO_4-P to 1.0 ppm PO_4-P in the input overland flow. At 1.0 ppm, however, the standing crop of organic detritus exceeded 3 kg/m^2, and approached 4 kg/m^2 in early February

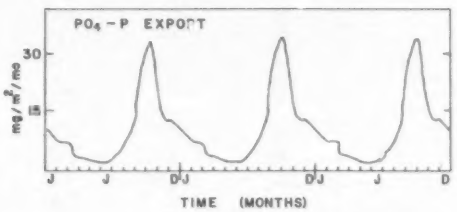

FIG. 8.—Temporal Pattern of Export of Dissolved Ortho-Phosphate Phosphorus from Marsh Basin under High Load Conditions (10 mg/m^2/month = 0.089 lb/acre/month)

just prior to drawdown. Further increases in organic detritus would result in a flush or organic material to the river during high-intensity rainfalls, with consequent high BOD loadings downstream. In addition, the peak plant community standing crop (1,500 g/m^2) and forage fish biomass (3 g dry weight/m^2) represent reasonable maxima for a functional marsh community, e.g., compare the value of 1,700 g/m^2 for bulrush community near Lake Okeechobee (Nordlie, et al., unpublished). For these reasons, a concentration of 1.0 ppm dissolved PO_4-P, corresponding to an inorganic P loading factor of 4.8 g/m^2/yr, was selected for further exploration.

Fig. 8 sets forth the time-varying export rate of dissolved phosphorus under high load conditions. Peak export occurs in October, when the load is highest (assuming a continuation of the natural hydroperiod) and the growing season for annual plants has passed. A total accounting of phosphorus export, using computer integration of the variables, yielded 0.22 g/m^2 of dissolved phosphorus plus 0.9 g/m^2 of organic phosphorus leaving the marsh each year. Comparing this to the yearly input loadings of 4.8 g/m^2 dissolved and 0.096 g/m^2/yr organic phosphorus (4,800 l/m^2/yr × 0.02 mg/l), we find that net absorption accounts for some 77% of the extrinsic load. (This accounting ignores the

"intrinsic" rainfall loading of 0.68 $g/m^2/yr$ of P). Phosphorus that leaves the marsh has also changed form: only 2% of the input load is in the form of organic phosphorus, but 80% of the phosphorus exported from the marsh is in organic form. This factor alone might reduce the likelihood of algal blooms in downstream water bodies, because organically bound phosphorus is relatively unavailable to algae until acted upon by a decomposition food chain.

Finite Difference Simulation of Wet Season Water Quality Effects.—Constant constituent source/sink terms from the ecosystem simulations of high load

TABLE 1.—Summary of Marsh Water-Quality Results, Finite Difference Models of Marsh during Wet Season

Load distribution (1)	Depth, in feet (2)	Flow, in cubic feet per second (3)	Residence time, in days (4)	$\dot{m}_o/\dot{m}_i$		
				c_1 (5)	c_2 (6)	c_3 (7)
100% P	1	5	15	4.75	5.45	0.100
		10	8	3.86	4.40	0.095
		50	1.9	1.81	1.96	0.295
	2	10	15.5	3.84	4.36	0.050
		20	7.5	2.84	3.18	0.045
		100	1.65	1.43	1.50	0.334
	4	20	16	2.75	3.10	0.025
		40	8	2.00	2.21	0.025
		200	1.65	1.17	1.23	0.300
75% NPS, 25% PS	2	10	27	3.80	4.35	0.075
		20	14	2.94	3.30	0.100
		100	2.9	1.50	1.60	0.336
	4	20	27	2.80	3.16	0.045
		40	14	2.14	2.35	0.084
		200	2.9	1.23	1.27	0.330
100% NPS	2	10	45	3.55	4.05	0.080
		20	24	2.71	3.04	0.120
		100	4.75	1.49	1.57	0.375
	4	20	45	2.65	3.00	0.055
		40	24	2.06	2.26	0.100
		200	4.75	1.23	1.26	0.370

Note: 1 ft = 0.305 m; 1 cfs = 0.02932 m^3/s.

conditions were coupled to typical wet-season hydrologic conditions (steady inputs) [June rainfall, evaporation rates, and water-quality data supplied by the local Flood Control District (FCD) (unpublished)] in order to evaluate the effects of flow depth, discharge, and residence time on water quality in restored marshes. Some 49 combinations of flow characteristics were evaluated with the finite difference models. The mass flux ratio [ratio of flux of constituent leaving the marsh $\dot{m}_o$, divided by total mass flux entering the marsh $\dot{m}_i$ (combined PS and NPS)] was used as an indicator of water-quality effects. The mass flux ratio for dissolved phosphate decreased with time and stabilized at some

value less than one in all cases, whereas the ratios for detrital phosphorus and organic materials increased over time and stabilized at values greater than one. The mass flux ratio for dissolved P generally stabilized within 6 (simulated) days; for detrital constituents the stabilization time was longer. Some typical results are given in Table 1, which lists the mean flow depth ($\bar{D}$), total flow rate, residence time, and $\dot{m}_o/\dot{m}_i$ of the constituents for several examples of PS/NPS load distribution.

Effect of Residence Time.—The mass flux ratio for a given constituent is determined by both T_r (residence time) and the rate at which constituent concentrations are altered by nonconservative production and decay mechanisms. These factors codetermine both the stable value of the mass flux ratio and the stabilization time. Residence time had a major impact on water quality when the residence time was the same as or shorter than the time required to stabilize production and decay mechanisms. However, increases in the residence time beyond that required for production/decay stability had little effect on water quality.

For example, consider the results shown in Table 1 for constituent c_1. For a 100% PS loading with $\bar{D} = 2$ ft, decreasing the flow rate from 100 cfs–20 cfs increased the mass flux ratio from 1.43 to 2.84 and increased the residence time from 1.65 days to 7.5 days. The mass flux ratios stabilized after 1.6 days and 7.5 days for $Q = 100$ cfs and $Q = 20$ cfs, respectively: the residence time is the dominant factor governing water quality. Next, consider $\bar{D} = 2$ ft and $Q = 20$ cfs with a 100% NPS loading. In this case, the mass flux ratio is 2.71, with a corresponding residence time of 24 days. Compare this value of the mass flux ratio (2.71), with the value of 2.84 given for the corresponding 100% PS loading in the previous example. The increase in residence time from 7.5 days to 24 days now has little effect on water quality. This apparent inconsistency is explained by the fact that only 12 days were required to stabilize the mass flux ratio for the 100% NPS loading; this is half the calculated residence time. Thus, nonconservative production and decay mechanisms generated a stable water quality well before the residence time of the water mass had elapsed.

Effect of Flow Depth.—Variations in the mean depth of flow across the marsh had a perceptible effect on the mass flux ratios. This was unsurprising, since the nonconservative source/sink terms were in part a function of depth. An increase in depth resulted in a decrease in $\dot{m}_o/\dot{m}_i$. Thus, the deeper waters are more desirable for water-quality improvement because, for a given V/Q ratio, they reduce the amount of constituent exported. This effect was particularly noticeable for c_1 and c_2, the detrital constituents.

Effect of Flow Distribution.—The distribution of flow into the marsh as either PS or NPS loadings, or combinations thereof, had little effect on water quality. The main difference was an increase in residence time under NPS loadings. However, because of the dominance of nonconservative production/decay mechanisms, corresponding changes in the mass flux ratio did not occur. In general, an NPS gave a slight decrease in the mass flux ratio for detrital constituents c_1 and c_2 and an increase in the mass flux ratio for dissolved phosphorus c_3.

Application of Results to C-38

One objective of this study was to develop criteria for restoration and

management of an active marsh system in the lower Kissimmee River basin. The restoration plan was based on predicted water-quality improvements. Total P was used as a control variable because the ameliorative significance of conversion of dissolved to detrital phosphorus was uncertain. The mass flux ratio for *total* phosphorus depends on the distribution between forms in the inflowing waters as well as on events in the marsh. Upland water entering the marshes would be composed of 90% dissolved phosphorus and 10% detrital phosphorus (unpublished FCD data for upper reaches of Chandler Slough). This distribution was used, along with computed flux ratios for constituents (examples in Table 1), to obtain $\dot{m}_o/\dot{m}_i$ values for total P as a weighted sum of constituent values [0.1 ($\dot{m}_o/\dot{m}_i$, detrital) + 0.9 ($\dot{m}_o/\dot{m}_i$, dissolved)]. A sample plot (PS) of the mass flux ratio for total P versus residence time is given in Fig. 9. These curves show that there is an optimum residence time, and therefore an optimum V/Q, for which the mass flux ratio for total P is at a minimum. For short residence times, $\dot{m}_o/\dot{m}_i$ is large with most of the export load in the dissolved form. As the residence time increases, dissolved phosphorus is

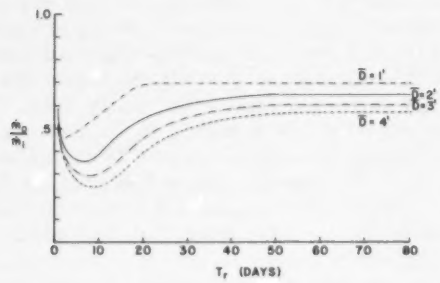

FIG. 9.—Plot of Stabilized Mass Flux Ratio Versus Residence Time (T_r) for Total Phosphorus under 100% PS Loading

taken up in the marsh faster than detrital phosphorus is produced, and $\dot{m}_o/\dot{m}_i$ decreases to a minimum. The curve then increases as the absorption of dissolved phosphorus slows and increased production of detrital phosphorus begins to dominate the system response. For long residence times, $\dot{m}_o/\dot{m}_i$ stabilizes for both constituents and the curve levels off. Thus, for *short* residence times the phosphorus exiting the marsh is predominantly *dissolved*, whereas the *long* residence times phosphorus exiting the marsh is predominantly *detrital*. Fig. 9 also shows that increases in the mean depth of flow reduce the mass flux ratio. The greatest decrease in $\dot{m}_o/\dot{m}_i$ follows an increase in $\bar{D}$ from 1 ft to 2 ft. This suggests that a minimum $\bar{D}$ of 2 ft be maintained on the restored marsh.

These results were used to devise a marsh restoration scheme. First, the mean depth of flow on the restored marsh was related to the regulated pool stage for each PU in the lower basin. Then, for selected pool elevations, plan areas and water volumes of restored marshes were estimated. Discharges calculated by Bedient (2) were used to determine flows across the marsh and

the percentage distribution of cumulative PS and NPS loads. Residence times were then determined from Fig. 5. Finally, from $\bar{D}$ and T_r, the effects of the restored marsh on total phosphorus were determined using curves similar to Fig. 9.

Marsh Restoration Scheme.—A preliminary evaluation showed that useful combinations of flow depth, storage volume, and discharge for a restored marsh could be achieved within the framework of the existing C-38 system. The marsh restoration scheme thus required minimal changes in existing structures and retained the flood routing capabilities of the system. The proposed scheme required that all flows introduced from upland sources within each PU be routed across the restored marsh to a marsh outlet structure in the tie-back levee at the lower end of the PU. The basic features of the restoration scheme were as follows:

1. A revised regulation schedule that would vary pool stages in C-38 over a range extending from below presently maintained levels to an elevation between 2 ft and 3.5 ft above present levels. The upper limit, which would apply during the wet season, was determined by marsh water-quality considerations. A viable marsh would need a slow autumn dry down and a dry period of approx 2 months to allow soil formation and germination of annual plants. The "excess" storage in PU 13-17 resulting from a 2-ft increase in pool stages could be routed to Lake Okeechobee in less than 10 hr (16).
2. Marsh outlet flow-control structures in the tie-back levees would control the flow of water from pool to pool, thereby encouraging water to flow across the marsh rather than down C-38. Marsh outlet structures should be designed to accommodate the flow entering the pool from upland sources. Except during some months of unusually wet years, all drainage flow for each PU would pass through these structures, with the channelized flow from the upper pools passing through the primary structure in C-38. The primary structures would also remain available for flood-control purposes. Existing auxiliary flow-control structures in the tie-back levees could be modified for use as marsh outlet control structures.
3. Redistribution of existing spoil and removal of dikes within restored marsh would be done selectively to maximize the available marsh acreage at a given pool stage and to enhance flow across the marsh.
4. Modification of C-38 primary control structures to accommodate increased pool elevations is needed. At present the primary control structures are unable to regulate (except temporarily) pool elevations above design values. They would need modification to handle the increased wet season pool elevations.

Water-Quality Benefits of Marsh Restoration.—To estimate the water-quality benefits of marsh restoration, the expected mean depth of flow and area of marsh were related to the regulated pool stage. The area of inundation was estimated from topographically controlled aerial mosaics. Average elevations for the part of the flood plain inundated by increases in pool stage were determined from average transverse elevations across the flood plain. Potential wet season marsh acreage (all pools combined) increased from 6,420 acres ((26,000,000 m^2) under the present schedule to 16,490 acres (66,740,000 m^2) with a 2-ft (0.6-m) increase, and to 29,396 acres (118,970,000 m^2) with a 3.5-ft (1.1-m) increase

(values of marsh acreage corrected for the area lost to dredge spoil using as-built conditions).

The potential flow across the restored marsh and its distribution as PS and NPS were obtained from Ref. 2. The PS loadings ranged from 17%–65% of total flow in the various PU. Curves like those in Fig. 9 were constructed for the source-load distribution of each PU in the lower basin. These discharges and source distributions were coupled to the area of inundation and flow-depth data to determine residence time for maximum, minimum, and mean flow conditions, e.g., maximum wet season upland flow for PU 15 was 387 cfs (11.0 m^3/s) (October, 1969), with 75% as a NPS discharge. This value of Q_{NP}/Q_{TOT} gave a residence time of 2.52 V/Q (Fig. 5). For $\bar{D}$ = 2 ft (0.6 m), V was 4.45×10^8 cu ft (1.26×10^7 m^3) in PU 15. Thus, for Q = 387 cfs (11.0 m^3/s) the residence time was 2.52 V/Q = 33.5 days. The estimated phosphorus transformation and capture dynamics resulting from marsh restoration at a mean flow depth of 2 ft (0.6 m) and average flows are given in Table 2. The average for the five planning units gives a total load reduction of 45% and a transformation

TABLE 2.—Changes in Dissolved, Detrital, and Total Phosphorus Resulting from Marsh Restoration, as percentages

PU (1)	Decrease dissolved P (2)	Increase detrital P (3)	Decrease in total P (4)
13	92	525	47
14	82	460	57
15	93	565	40
16	93	510	41
17	93	528	40

Note: Analysis assumed an initial load composed of 90% dissolved phosphorus and 10% detrital phosphorus.

from an input distribution of 90% dissolved (10% detrital) to 16% dissolved (84% detrital) forms in water released from the marshes.

Summary and Conclusions

In conclusion, it appears that natural flood-plain marshes can sequester approx 50% of peak wet season nutrient loadings and approx 75% of total yearly load, at least when the load is primarily in dissolved inorganic forms. Equivalent benefits could be expected from extant marshes in the Kissimmee basin if operated under a prechannelization hydrologic regimen, with a reduction of total phosphorus exports from the basin to Lake Okeechobee.

Whether operation of extant Kissimmee marshlands with such a natural hydroperiod is possible under current conditions is an open question. Peak basin rainfalls are no longer subject to much upland detention in many areas of the basin, so that the Kissimmee hydroperiod crest has shifted some 3 months–4 months forward from October to June and July (12). In addition, dry season

water table levels have declined. Private conversations with FCD personnel indicated that C-38 is usually an influent stream (exporting water to the flood plain) during most of the dry season. Analysis of prechannelization hydrologic data clearly demonstrated that this was *not* the case prior to channelization.

The consequences of this shift and sharpening of the Kissimmee hydroperiod are not trivial to the feasibility of using Kissimmee marshes for water-quality improvement. Field studies (FCD, unpublished) of nutrient dynamics in extant Kissimmee wetlands (notably Chandler Slough) have shown a low detention time of water on the marsh "due to sparseness of vegetation," apparently with a consequent pulse of phosphorus release from the marsh early in the wet season. The natural (prechannelization) marshes were probably well developed by this time. It seems likely that spring development of the marshes has been considerably retarded in recent years by low dry season water tables. This effect would be compounded by the shift in peak discharges, tending to maximize loadings at a time of minimum absorptive capacity. Current (FCD) experience in Chandler Slough also indicates a high detention time and low phosphorus release around the month of October when the model predicts a peak discharge of ortho-phosphate from the marshes. This "discrepancy" is a consequence of altered hydroperiod and vegetation characteristics. Examination of Fig. 7 will show that, for a natural marsh loaded at 0.05 ppm phosphorus, peak ortho-phosphate concentrations in waters exiting the marsh occur in Marsh as a consequence of dry season oxidation of marsh sediments. The October peak concentrations and peak exports for high load conditions (Fig. 8) result from the dominance of October extrinsic loadings with a high (1 ppm PO_4-P) phosphorus concentration in the input stream. Even so, the marsh export water is improved in quality to a point comparable with water now found in C-38. In other words, the longer detention times and low phosphorus export found in Chandler Slough during the fall are typical of prechannelization marshes as shown in the model, but the early wet season phenomena of sparse vegetation, short detention times, and net phosphorus release are primarily a consequence of drainage. Indeed, Lee, et al. (17) have concluded that drained marshes may frequently be significant net contributors of nitrogen and phosphorus to receiving water bodies through oxidation of previously sequestered organic deposits. Unconsidered attempts to use heavily modified drained wetlands for water-quality control thus appear ill advised, and can easily lead to biased conclusions concerning the value of natural wetlands for water-quality management.

In the Kissimmee basin, careful hydroperiod regulation and pilot studies would be needed to establish marsh management programs that are ecologically sound. An analytic tool like the model developed in this report would help predict consequences of management strategies. Such a model should incorporate the effect of large variations in vegetation density on hydraulic friction coefficients, if abbreviated hydroperiods are a necessary feature of economically viable management schemes.

Another question requiring resolution is the useful lifetime of marshes utilized for water-quality renovation. It is distinctly possible that when a marsh surface comes into equilibrium with the average water table, a steady-state balance of phosphorus input and output may be achieved. In this study, genesis of stabilized marsh sediments proceeded, under high load conditions, at no more than approx 1 kg of organic matter/m^2/yr (4.46 tons of organic matter/acre/yr).

Taking representative peats (4) to represent reasonable expectations of the soil formed (i.e., bulk density of 0.25 g/cm^3 and 80% organic matter) amounts to an accretion rate of 0.5 cm/yr or 1 ft in 61 yr. This value is about four times the peat formation rate of sawgrass everglades marsh, an oligotrophic marsh type (6).

Even under steady-state conditions, benefits to Lake Okeechobee could be expected from transformation of ortho-phosphate to organic phosphates less available to nuisance algae and from delay of peak loads to late fall or the following dry season, depending on the management hydroperiod utilized and the loading rates. In addition, water flowing through the marsh might contact subterranean limestone strata, leading to geochemical deposition of phosphorus in deep layers by precipitation of calcium phosphates (13). Also, pre-existing soil beds might sequester phosphorus from infiltration waters for an extended period (11). These processes could result in essentially permanent removal of phosphorus from the effluent, as well as providing automatic safe disposal. Unlike many wastewater renovation processes, treatment with natural wetlands need not merely convert a wastewater problem into a solid-waste problem.

Appendix I.—Model Equations

Ecosystem Model

Total water storage on marsh W (including soil storage), in millimeters of water:

$$\frac{dW}{dt} = R + U - E - G - S; \quad E = P \exp\,[-K_3(W_s - W)(W < W_s)];$$

$$G = K_1\,[W(W < W_s) + W_s(W > W_s)]; \quad S = K_2(W - W_s)^2(W > W_s) \quad . \quad . \quad . \quad (2)$$

in which R = rainfall, in millimeters per month; U = input via upland runoff, in millimeters per month; P = pan evaporation; E = actual E-T; G = ground-water export; S = surface-water export; P = monthly pan evaporation rates; W_s = saturated soil-water content available to runoff (G) and E (200 mm); $W > W_s = 1$ when $W > W_s$ (i.e., free-standing water is present on marsh), 0 when $W < W_s$; $W < W_s = 1$ when free water surface is below ground level, 0 otherwise; and K_1, K_2, K_3 = parameters estimated from Ref. 5 as 1.52/month, 1.61×10^{-3}/mm/month, and 3.35×10^{-3}/mm, respectively.

Inorganic phosphorus dissolved in marsh water P_w, in milligrams of phosphorus per square meter:

$$\frac{dP_w}{dt} = C_r R + C_u U + P_D D_o^{-1}(O_x) - P_c B_p - \alpha^{-1} P_c (G + S);$$

$$O_x = [K_5 + K_6(W_s - W)(W < W_s)]\,D_o; \quad B_p = K_7 + K_8(S \wedge DD) \quad . \quad . \quad . \quad . \quad (3)$$

in which $P_c = P_w / W$ (ambient concentration, in milligrams of phosphorus per liter); C_r = concentration in rainfall (0.056 ppm P); C_u = concentration in upland flows; P_D = detrital (organic, particulate) phosphorus, in milligrams of phosphorus per square meter; O_x = oxidation rate of detrital organic matter; K_5 = rate coefficient, decay of detrital organic matter under flooded conditions, 6.57×10^{-2}/month; K_6 = coefficient for increased oxidation in damp soil

zones as water table recedes below ground level, 5.92×10^{-4}/mm/month; D_o = detrital organic matter, in milligrams per square meter; α = effective mixing ratio (dimensionless parameter for intermodel calibration of basin transport processes); B_p = uptake coefficient of macrophyte community; K_7 = phosphorus uptake coefficient, perennials, 2.325×10^4 mm/month; K_8 = phosphorus uptake coefficient, annuals, 7.75×10^3 mm/month; and $(S \wedge DD) = 1$ when a dry down ($W < W_s$) of at least 6 weeks duration (to allow germination of annuals) occurs during the growing season S, 0 otherwise.

Biomass of perennial and annual plant community B, in milligrams of organic matter per square meter:

$$\frac{dB}{dt} = [K_p + K_a(S \wedge DD)]EP_B - K_r B - K_L B \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which P_B = phosphorus in plant tissues, in milligrams of phosphorus per square meter; K_p = growth coefficient of perennial plants, 4.28/mm; K_a = growth coefficient of annual plants, 2.43/mm; K_r = respiration rate of macrophytes, 3.07/month; and K_L = litter production coefficient, 0.5/month.

Phosphorus in plant tissues P_B, in milligrams of phosphorus per square meter:

$$\frac{dP_B}{dt} = P_C B_P - K_L P_B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Detrital organic matter D_o, in milligrams per square meter:

$$\frac{dD_o}{dt} = K_L B + D_u U - K_9 D_o S - O_x - K_c D_o (W < W_s) \quad \ldots\ldots\ldots\ldots (6)$$

in which D_u = detrital carbon concentration in inflowing waters (2.5 ppm TOC); K_9 = export coefficient for detritus, 5.0×10^{-5}/mm; and K_c = compaction coefficient for incorporation of detrital materials into soil structure, 0.20/month.

Detrital (organic, particulate) phosphorus P_D, in milligrams of phosphorus per square meter:

$$\frac{dP_D}{dt} = P_{DU}(U) + K_L P_B - O_x P_D D_o^{-1} - K_c (W < W_s) P_D - K_9 S P_D \quad \ldots\ldots (7)$$

in which P_{DU} = organic P in upland inflows, .02 mg/l.

Forage fish biomass F, in milligrams of dry weight per square meter:

$$\frac{dF}{dt} = K_F P_D (W - W_s)(W > W_s) - K_{FR} F \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which K_F = ingestion coefficient of forage fish community, 2.39×10^{-2}/mm/month; and K_{FR} = respiration of fish community, 1.05/month.

Equations Solved by Hydromechanics Model

Equation of motion in the x direction (solved for q_x):

$$\frac{\partial q_x}{\partial t} = (R - E_v - S) q_x D^{-1} - 0.5\, q_x D^{-2} (0.25 f |q| + K_x \gamma^{-1} |q_x|)$$

$$- \left(2q_x \frac{\partial q_x}{\partial x} + q_y \frac{\partial q_x}{\partial y}\right) D^{-1} - (gD - q_x^2 D^{-2}) \frac{\partial \eta}{\partial x}$$

$$+ q_x q_y D^{-2} \frac{\partial \eta}{\partial y} - q_x D^{-1} \frac{\partial q_y}{\partial y} + \epsilon \frac{\partial^2 q_x}{\partial y^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Equation of motion in the y direction (solved for q_y):

$$\frac{\partial q_y}{\partial t} = (R - E_v - S) q_y D^{-1} - 0.5 q_y D^{-2} (0.25 f |q| + K_y \gamma^{-1} |q_y|)$$

$$- \left(2q_y \frac{\partial q_y}{\partial y} + q_x \frac{\partial q_y}{\partial x}\right) D^{-1} - (gD - q_y^2 D^{-2}) \frac{\partial \eta}{\partial y}$$

$$+ q_x q_y D^{-2} \frac{\partial \eta}{\partial x} - q_y D^{-1} \frac{\partial q_x}{\partial x} - \epsilon \frac{\partial^2 q_y}{\partial x^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Equation of continuity (solved for η):

$$R - E_v - S = \frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

in which $D = \eta + h$ = total depth of water; h = stillwater depth; $\gamma = \rho g$ = specific weight of water; ϵ = eddy viscosity; R, E_v, S = rainfall, evaporation, and seepage rates, respectively; f = Darcy-Weisbach friction factor; K_x, K_y = local loss coefficients for regions of flow transition; and $q = (q_x^2 + q_y^2)^{1/2}$.

Transport Diffusion Equation

$$\frac{\partial \bar{c}}{\partial t} = RD^{-1}(c_R - \bar{c}) + E_v D^{-1} \bar{c} + SD^{-1}(\bar{c} - c_s) + \sum_n P_n - \frac{\partial}{\partial x}(\bar{u}\bar{c})$$

$$- \frac{\partial}{\partial y}(\bar{v}\bar{c}) + \bar{c}\frac{\partial \bar{u}}{\partial x} + \bar{c}\frac{\partial \bar{v}}{\partial y} + A_1 \frac{\partial^2 \bar{c}}{\partial x^2} + A_2 \frac{\partial^2 \bar{c}}{\partial x \partial y} + A_3 \frac{\partial^2 \bar{c}}{\partial y^2} \quad \ldots\ldots\ldots (12)$$

in which the functions A_1, A_2, and A_3 represent two-dimensional anisotropic dispersion coefficients developed from Elder (10) by Taylor and Dean (25). In this formalism

$$A_1 = [0.125 f (q_x^2 + q_y^2)]^{1/2} (5.9 - 5.7 \sin^2 \beta);$$

$$A_2 = 11.4 [0.125 f (q_x^2 + q_y^2)]^{1/2} \sin \beta \cos \beta;$$

$$A_3 = [0.125 f (q_x^2 + q_y^2)]^{1/2} (5.9 - 5.7 \cos^2 \beta);$$

$$\beta = \tan^{-1}(q_y q_x^{-1}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

and c_R = constituent concentration in rainfall; c_s = constituent concentration in seepage [when $S > 0$ (seepage from water column into ground), $c_s = \bar{c}$]; and $\bar{c}$ = vertically averaged constituent concentration.

The P_n source/sink terms (derived from ecosystem model):

Detrital carbon, c_1

$$P_1 = -K_{fc} c_1 - w_s D^{-1} c_1 + (DLFO) D^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Detrital phosphorus, c_2

$$P_2 = -K_{fc}c_2 - w_s D^{-1}c_2 + (DLFI)D^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Dissolved phosphorus, c_3

$$P_3 = K_{fc}c_2 - K_{ev}E_v D^{-1}c_3 - K_{up}c_3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

in which K_{fc} = oxidation rate of detrital material and associated release of detrital forms of nutrients to dissolved forms in the water column, 4.8×10^{-9}/sec; w_s = settling velocity of detrital material, 6.58×10^{-5} cm/s; $DLFO$ = litter-fall production of detritus, ecosystem value was 150 g organic matter/m^2/month; $DLFI$ = litter-fall production of detrital phosphorus, ecosystem value was 0.2 g/m^2/month; K_{ev} = coefficient for uptake of dissolved P via macrophyte transpiration stream, 1.0 (dimensionless); and K_{up} = macrophyte active uptake coefficient, 1.3×10^{-5}/sec.

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14540 NUTRIENT-UPTAKE MODEL IN MARSH ECOSYSTEMS

KEY WORDS: **Aquatic plants;** Computers; **Ecology;** Environmental engineering; **Flood control; Marshes;** Models; Natural resources; Regional planning; **Rivers; Water quality**

ABSTRACT: Mechanistic models of nutrient dynamics in natural wetlands were developed and applied in a study of Kissimmee River (Florida) flood-plain marshes. The models describe hydrodynamics and transport diffusion in wetland basins; and the ecological processes of nutrient uptake, conversion to organic forms, and release from the marsh to a receiving water body. Results of computer simulations suggested that more than 50% of dissolved phosphorus loadings could be permanently captured by the marsh ecosystem, at least up to a loading rate of 5 $g/m^2/yr$. In addition, 80% to 90% of the phosphorus exported from the marsh would be transformed from dissolved to detrital forms, and would therefore be relatively unavailable to nuisance algae. The simulations suggested that consolidated peat would be laid down at a rate of approx 0.5 cm/yr, giving a useful life of the marsh of perhaps 50 yr to 100 yr.

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